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Secure Wireless Information and Power Transfer Based on Tilt Adaptation in 3-D Massive MIMO Systems

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ABSTRACT In this paper, we investigate a secure transmission algorithm exploiting the vertical domain for simultaneous wireless information and power transfer (SWIPT) in a massive multiple-input multiple-output system over Rician fading channels. Each user adopts the power splitting (PS) technique to separate information and energy, which is regarded as a potential eavesdropper (ED) for the intended user. We consider the scenario, where at least one ED has the same angle of departure with the intended user. The base station (BS) applies artificial noise (AN) and deploys 3-D directional antennas to enhance the secure rate and energy transfer by adjusting the antenna tilt adaptively. We first derive the approximate ergodic achievable secrecy rate and harvested power. Based on these approximations, the optimization problem is formulated to minimize the total transmit power with individual secrecy rate and harvested power targets. We propose an iterative algorithm to jointly optimizing the BS antenna tilt, AN covariance, power allocation, and PS ratios. The numerical results verify that the approximate secrecy rate is very close to the actual values and show that the performance of the proposal approaches that of the optimal solutions from the brute-force search and outperforms the 2-D and conventional 3-D schemes, which proves the significant role of tilt adaptation in the secure SWIPT.

INDEX TERMS Antenna tilt, massive MIMO, physical layer security, SWIPT.

I. INTRODUCTION

Simultaneous wireless information and power transfer (SWIPT) was first proposed in [1] and has been widely studied in various wireless communication systems in recent years [2]–[5]. It provides reliable and perpetual energy support for power-limited wireless devices to avoid wireline charging or battery replacement, so the sustainability and mobility of wireless communications are ensured. Moreover, the spectral efficiency of communication systems is also enhanced, since information and power signals are carried by the same radio frequency wave. To realize SWIPT in practice, the received signal is spilt into two distinct parts, which are information decoding (ID) and energy harvesting (EH), respectively. Power splitting (PS) is one practical technique for co-located information and energy receivers, which achieves instantaneous SWIPT and reduces process latency [6].

However, due to the open nature of wireless channels, potential information leakage could happen during SWIPT. Each user is the potential eavesdropper (ED) to the intended user who is meant to receive the information from the base station (BS). Conventional upper-layer encryption techniques can be applied for security, but they have high computational complexity and consume a great deal of energy. The transmitted energy which is originally used to charge the devices now is applied for encryption and decryption. So, cryptography is not very economical and energy efficient. Physical-layer secrecy is an effective alternative to guarantee secure communication. The structured redundancy is added into the transmitted signal for the intended user who can decode the confidential message, and the EDs retrieve almost nothing [7]. In SWIPT systems, this confusing signal to the EDs can be harvested by users as a power source. Artificial noise (AN) is one of the appealing approaches to confuse the EDs deliberately [8]. Besides, transmission design can help to focus the transmitted signal in the direction of the intended user and prevent power leakage to the EDs.

Massive multiple-input multiple-output (MIMO) system offers extremely narrow beams directed toward users with hundreds of antennas deployed at the BS [9]. It can compensate for propagation losses and improve power transfer efficiency of SWIPT [10]. Furthermore, it has great potential of physical layer security [11]. Secure SWIPT has been studied in massive MIMO systems [12]–[15]. In [12], the benefits of massive MIMO enabled heterogeneous cloud radio access network is investigated in terms of secrecy and energy efficiency. In secure massive MIMO systems, the passive EDs have a negligible effect on the secrecy capacity, since a tremendous array gain and channel hardening brought by massive MIMO systems render the signal strength of the intended user much larger than that of the EDs. The countermeasure taken by the EDs is to stay in an active mode instead of a passive one. The contribution of [13] is the transmission optimization with active energy harvester which is capable of legitimately harvesting energy and illegitimately and actively eavesdropping the signal for the intended user. However, the secrecy capacity can still be compromised with passive EDs in some scenarios. For example, the channels of the intended user and the EDs are correlated. The work in [14] addresses the ergodic secrecy rate maximization problem with a harvested energy constraint over channels with transmit correlations, and optimizes the transmit covariance. It shows that the harvested energy increases and the secrecy rate decreases when the transmit correlation increases. On the other hand, despite the independent channels, transceiver hardware impairments can also degrade the secrecy performance caused by low-cost components in massive MIMO systems for controlling the expenditures of mobile operators. The authors in [15] study the effect of phase noise on SWIPT. Since uplink training is affected by phase drift, the secrecy rate decreases as the phase noise variance increases, which results in information leakage. With line-of-sight (LoS) channels, if the EDs are at the same angle-of-departure (AoD) with the intended user, the EDs will receive correlated signals and the secrecy rate will be damaged. In this paper, we consider this scenario and use three-dimensional (3-D) antenna technique to solve this problem.

In 3-D massive MIMO systems, the BS employs 3-D directional antennas to exploit both the horizontal and vertical domains such that the beam could be more directional [16]. Since the transmission-distance-to-BS-height ratio in SWIPT is usually smaller than that in a conventional macro cell, the vertical scale of SWIPT is more comparable with the horizontal one, and thus is more critical in SWIPT than in the macro cell. The authors in [17] apply the 3-D massive MIMO for SWIPT and analyze the performance with 3-D sectorized antennas. They show that the vertical domain can offer a more accurate beam steering which is beneficial for both information and power transfer. To the best of our knowledge, 3-D massive MIMO has not been investigated for secure SWIPT yet.

In this paper, we exploit the vertical domain to ensure secure communications in massive MIMO SWIPT systems with Rician fading channels. Each user adopts PS technique to separate the information and energy, and is seen as the potential ED for the intended user who is expected to receive the confidential message. The BS applies AN to confuse eavesdropping. We assume that at least one ED has the same AoD with the intended user, so the received signal at this kind of ED is highly correlated. The secrecy rate is thus degraded. We deploy the BS with 3-D directional antennas and the antenna tilt is adjusted to alleviate this problem. The BS adapts the antenna tilt based on users' locations such that the vertical domain is exploited and notable performance gains are achieved [18]–[20]. We first derive the approximate secrecy rate and harvested power. Based on these approximations, the optimization problem is formulated to minimize the transmit power with the secrecy rate and harvested energy targets. We propose an iterative algorithm to jointly optimize the antenna tilt, power allocation, AN covariance, and PS ratios. Numerical results verify that the approximate secrecy rate is very close to the actual value, and show that our proposal approaches to the optimum from the brute-force search and outperforms the two-dimensional (2-D) and conventional 3-D MIMO schemes.

II. SYSTEM MODEL

Consider a single-cell massive MIMO system. One BS deploys M antennas and U single-antenna users are active in this cell, where $M \gg U$. The BS sends data and energy to users at the same time, which constitutes SWIPT. The sent message for the intended user is confidential and other users are regarded as potential EDs. In order to ensure the security of the confidential messages, AN is designed in the transmitted signal to confuse those potential EDs.

A. SIGNAL MODEL

Massive MIMO simplifies the signal processing. Even with a low-complexity transmission scheme such as matched filter (MF) precoding, it is able to achieve satisfying performance. MF precoding can provide asymptotically optimal performance for information transmission [9] and energy transfer [10]. Hence, we apply MF precoding at the BS for transmission. The transmitted signal is

$$\mathbf{x} = \sum_{u=1}^{U} \sqrt{\alpha_u} \frac{\mathbf{g}_u}{\|\mathbf{g}_u\|} s_u + \mathbf{v}, \tag{1}$$

where α_u is the allocated power for the u-th user, $\mathbf{g}_u \in \mathbb{C}^M$ represents the channel vector, $\frac{\mathbf{g}_u}{\|\mathbf{g}_u\|}$ is the normalized MF precoder, $s_u \sim \mathcal{CN}(0, 1)$ is the transmitted data symbol [21], $\mathbf{v} \in \mathbb{C}^M$ denotes the AN and is modeled as $\mathbf{v} \sim \mathcal{CN}(\mathbf{0}, \mathbf{V})$ where $\mathbf{V} = \mathbf{v}\mathbf{v}^H$ is the covariance matrix.

The received signal at the u-th user is

$$y_u = \mathbf{g}_u^H \left(\sum_{i=1}^{U} \sqrt{\alpha_i} \frac{\mathbf{g}_i}{\|\mathbf{g}_i\|} s_i + \mathbf{v} \right) + n_u, \tag{2}$$

where $n_u \sim \mathcal{CN}(0, \sigma_u^2)$ is the antenna noise. The PS technique is adopted by users. The signal for ID is [5]

$$y_u^{\mathrm{ID}} = \sqrt{\rho_u} \left(\mathbf{g}_u^H \sum_{i=1}^{U} \sqrt{\alpha_i} \frac{\mathbf{g}_i}{\|\mathbf{g}_i\|} s_i + \mathbf{g}_u^H \mathbf{v} + n_u \right) + z_u, \tag{3}$$

where ρ_u is the PS ratio, $z_u \sim \mathcal{CN}(0, \delta_u^2)$ is the additional noise caused by ID. The signal-to-interference-plus-noise ratio (SINR) of the u-th user is given by

$$\gamma_u = \frac{\rho_u \alpha_u \|\mathbf{g}_u\|^2}{\rho_u \sum_{i \neq u} \frac{\alpha_i |\mathbf{g}_u^H \mathbf{g}_i|^2}{\|\mathbf{g}_i\|^2} + \rho_u \mathrm{tr}(\mathbf{g}_u \mathbf{g}_u^H \mathbf{V}) + \rho_u \sigma_u^2 + \delta_u^2}. \tag{4}$$

The independent confidential message transmitted for the u-th user may be wiretapped by other users. For the u-th user, the other $U - 1$ users are potential EDs. The received SINR at the m-th user corresponding to the confidential message for the u-th user is expressed by

$$\gamma_{m,u} = \frac{\alpha_u \frac{|\mathbf{g}_m^H \mathbf{g}_u|^2}{\|\mathbf{g}_u\|^2}}{\sum_{i \neq u} \frac{\alpha_i |\mathbf{g}_m^H \mathbf{g}_i|^2}{\|\mathbf{g}_i\|^2} + \mathrm{tr}(\mathbf{g}_m \mathbf{g}_m^H \mathbf{V}) + \sigma_m^2}, \quad m \neq u. \tag{5}$$

The ergodic achievable individual secrecy rate of the u-th user is given by [22]

$$R_u = \left[r_u - \max_{\forall m, m \neq u} r_{m,u} \right]^+, \tag{6}$$

where $[x]^+ = \max(0, x)$, r_u is the ergodic achievable rate of the link between the BS and the u-th user, $r_{m,u}$ is the ergodic achievable rate of the link between the BS and the m-th user who is the ED associated with the u-th user. r_u and $r_{m,u}$ are respectively given by

$$r_u = \mathbb{E}\left[\log_2(1 + \gamma_u)\right], \tag{7}$$

and

$$r_{m,u} = \mathbb{E}\left[\log_2(1 + \gamma_{m,u})\right], \quad m \neq u. \tag{8}$$

The u-th user also harvests energy and the signal for EH is

$$y_u^{\mathrm{EH}} = \sqrt{1 - \rho_u} \left(\mathbf{g}_u^H \sum_{i=1}^{K} \sqrt{\alpha_i} \frac{\mathbf{g}_i}{\|\mathbf{g}_i\|} s_i + \mathbf{g}_u^H \mathbf{v} + n_u \right). \tag{9}$$

We assume that the noise in (9) is too small to be harvested. The harvested power of the u-th user is

$$E_u = \xi_u (1 - \rho_u) \mathbb{E}\left[\sum_{i=1}^{U} \alpha_i \frac{|\mathbf{g}_u^H \mathbf{g}_i|^2}{\|\mathbf{g}_i\|^2} + \mathrm{tr}(\mathbf{g}_u \mathbf{g}_u^H \mathbf{V}) \right], \tag{10}$$

where $\xi_k \in (0, 1]$ is the energy conversion efficiency.

B. CHANNEL MODEL

With 3-D directional antennas, the channel vector of the u-th user is

$$\mathbf{g}_u = \beta_u^{\frac{1}{2}}(\theta_{\mathrm{tilt}}) \mathbf{h}_u, \tag{11}$$

where $\mathbf{h}_u$ represents fast fading, $\beta_u(\theta_{\mathrm{tilt}})$ embraces the path gain including shadow fading, geometric attenuation and antenna gain, which is given by

$$\beta_u(\theta_{\mathrm{tilt}}) = \omega_u d_u^{-\upsilon} B_u(\theta_{\mathrm{tilt}}), \tag{12}$$

where θ_{tilt} is the antenna tilt, ω_u is the shadowing drawn from a log-normal distribution with standard deviation σ_{shad}, $d_u^{-\upsilon}$ denotes the path loss, d_u is the distance between the BS and the u-th user, υ is the path loss exponent, $B_u(\theta_{\mathrm{tilt}})$ is the antenna gain.

We assume that M antennas at the BS are in the plane parallel to the ground. Vertically stacked antenna elements are contained in each antenna and transmit the same signal with weights. Both element patterns and their weights determine the antenna pattern. The BS uses the 3-D directional antenna model and the antenna pattern in dBi scale is [23]

$$B_u(\theta_{\mathrm{tilt}}) = -\left\{ \min\left[12 \left(\frac{\phi_u}{\phi_{3\mathrm{dB}}} \right)^2, \mathrm{SLL}_{\mathrm{az}} \right] + \min\left[12 \left(\frac{\theta_u - \theta_{\mathrm{tilt}}}{\theta_{3\mathrm{dB}}} \right)^2, \mathrm{SLL}_{\mathrm{el}} \right] \right\}, \tag{13}$$

where ϕ_u is the horizontal angle between the x-axis and the connecting line of the u-th user and the BS in the horizontal plane, θ_u is the vertical angle between the horizon and the connecting line of the u-th user and the BS, θ_{tilt} is the tilt measured between the horizon and the beam peak, $\mathrm{SLL}_{\mathrm{az}}$ and $\mathrm{SLL}_{\mathrm{el}}$ are the sidelobe levels of the antenna patterns in the horizontal and vertical planes, respectively, $\phi_{3\mathrm{dB}}$ and $\theta_{3\mathrm{dB}}$ are the 3 dB beamwidths in the horizontal and vertical planes, respectively. The schematic illustration of these angles is shown in Fig. 1.

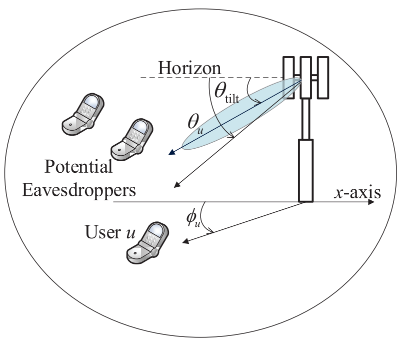

FIGURE 1. **Illustration of angles in the antenna pattern of the *u*-th user.**

In the practical scenario, a LOS component could exist between the BS and the user. In this paper, we take into account the LOS component and consider the Rician fading channel model. Thus, the fast fading $\mathbf{h}_u$ consists of a specular component accounting for the LOS signal and a Rayleigh-distributed random component corresponding to the diffused multipath signals. $\mathbf{h}_u$ can be written as [24]

$$\mathbf{h}_u = \sqrt{\frac{K_u}{K_u+1}}\bar{\mathbf{h}}_u + \sqrt{\frac{1}{K_u+1}}\mathbf{h}_{\omega,u}, \tag{14}$$

where K_u is the Rician K-factor of the u-th user, $\bar{\mathbf{h}}_u$ is the deterministic component of the u-th user, $\mathbf{h}_{\omega,u} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_M)$ is the random component, which is independent from each other. The deterministic component $\bar{\mathbf{h}}_u$ is [25]

$$\bar{\mathbf{h}}_u = [1, e^{-j2\pi\frac{\tau}{\lambda}\sin\psi_u}, \cdots, e^{-j2\pi(M-1)\frac{\tau}{\lambda}\sin\psi_u}]^T, \tag{15}$$

where τ is the distance between two adjacent antenna elements, λ is the carrier wavelength, $0 < \psi_u < 2\pi$ is the AoD with respect to the antenna array boresight direction. There are two properties of $\bar{\mathbf{h}}_u$ which will be used in deriving the main results of this paper, and we firstly present them in the lemma below.

Lemma 1: Let $\bar{\mathbf{h}}_u\bar{\mathbf{h}}_u^H = \mathbf{A}_u, \forall u$. Then

1) $\mathrm{tr}(\mathbf{A}_u) = M$;
2) When the m-th user has the same AoD with the u-th user, i.e., $\psi_u = \psi_m$ and $\bar{\mathbf{h}}_u = \bar{\mathbf{h}}_m$, we have

$$\mathrm{tr}(\mathbf{A}_u\mathbf{A}_m) = \mathrm{tr}(\mathbf{A}_u^2) = M^2, \quad m \neq u.$$

III. ANALYSIS OF SECRECY RATE AND HARVESTED POWER

In this section, we analyze the ergodic achievable individual secrecy rate and the harvested power in 3-D massive MIMO SWIPT systems with Rician channels. First, we establish a few key preliminary results.

Lemma 2: For the u-th user, we have

$$\mathbb{E}[\|\mathbf{g}_u\|^2] = \beta_u(\theta_{\mathrm{tilt}})M. \tag{16}$$

Proof: The result is obtained via (11) and (14). ■

Lemma 3: For two different users, i.e., the u-th user and the i-th user, $u \neq i$,

$$\mathbb{E}\left[\frac{|\mathbf{g}_u^H\mathbf{g}_i|^2}{\|\mathbf{g}_i\|^2}\right] \approx \ell_{i,u}\beta_u(\theta_{\mathrm{tilt}}), \tag{17}$$

where

$$\ell_{i,u} = \frac{K_iK_u\mathrm{tr}\,(\mathbf{A}_i\mathbf{A}_u) + K_uM}{M(K_i+1)(K_u+1)} + \frac{1}{K_u+1}. \tag{18}$$

Proof: See Appendix. ■

In order to obtain the ergodic achievable individual secrecy rate, we need to analyze the ergodic achievable rates of the intended user and the ED, respectively.

Theorem 1: We assume that the covariance matrix of the AN $\mathbf{V}$ has uniformly bounded spectral norm. The ergodic achievable rate of the link between the BS and the u-th user at ID in the 3-D massive MIMO SWIPT system with Rician channels is approximated by

$$r_u \approx \log_2(1+\tilde{\gamma}_u), \tag{19}$$

where

$$\tilde{\gamma}_u = \frac{\alpha_uM}{\sum_{i\neq u}\alpha_i\ell_{i,u} + \frac{K_u\mathrm{tr}(\mathbf{A}_u\mathbf{V})+\mathrm{tr}\mathbf{V}}{K_u+1} + \frac{\sigma_u^2}{\beta_u(\theta_{\mathrm{tilt}})} + \frac{\delta_u^2}{\rho_u\beta_u(\theta_{\mathrm{tilt}})}}. \tag{20}$$

Proof:

According to (4) and (7), the ergodic achievable rate of the u-th user is approximated by [26, Lemma 1] (21), as shown at the bottom of this page.

Assume that $\mathbf{V}$ has uniformly bounded spectral norm, with the similar procedure as the proof of Lemma 3 in Appendix VI, we have

$$\mathbb{E}[\mathrm{tr}(\mathbf{g}_u\mathbf{g}_u^H\mathbf{V})] = \frac{\beta_u(\theta_{\mathrm{tilt}})K_u\mathrm{tr}(\mathbf{A}_u\mathbf{V}) + \beta_u(\theta_{\mathrm{tilt}})\mathrm{tr}\mathbf{V}}{K_u+1}. \tag{22}$$

Combing Lemma 2, 3, and (22), we get (19). ■

Similarly, we get the approximate ergodic achievable rate of the ED in the following theorem.

Theorem 2: We assume that the covariance matrix of the AN $\mathbf{V}$ has uniformly bounded spectral norm. The ergodic achievable rate of the link between the BS and the m-th user who is the ED associated with the u-th user is approximated by

$$r_{m,u} \approx \log_2(1+\tilde{\gamma}_{m,u}), m \neq u, \tag{23}$$

where $\tilde{\gamma}_{m,u}$ is given by

$$\tilde{\gamma}_{m,u} = \frac{\alpha_u\left(\frac{K_uK_m\mathrm{tr}(\mathbf{A}_u\mathbf{A}_m)+K_mM}{M(K_u+1)(K_m+1)} + \frac{1}{K_m+1}\right)}{\sum_{i\neq u,m}\alpha_i\ell_{i,m} + \alpha_mM + \frac{K_m\mathrm{tr}(\mathbf{A}_m\mathbf{V})+\mathrm{tr}\mathbf{V}}{K_m+1} + \frac{\sigma_m^2}{\beta_m(\theta_{\mathrm{tilt}})}}. \tag{24}$$

Based on (6), Theorem 1, and 2, we approximate the secrecy rate as follows.

Theorem 3: We assume that the covariance matrix of the AN $\mathbf{V}$ has uniformly bounded spectral norm. The ergodic achievable secrecy rate of the u-th user is approximated by

$$\tilde{R}_u = \left[\log_2(1+\tilde{\gamma}_u) - \max_{\forall m, m\neq u}\log_2(1+\tilde{\gamma}_{m,u})\right]^+, \tag{25}$$

where $\tilde{\gamma}_u$ and $\tilde{\gamma}_{m,u}$ are given by (20) and (24), respectively.

The harvested power in (10) is obtained in the following theorem by using Lemma 1, 2, 3, and (22).

$$r_u \approx \log_2\left(1 + \frac{\rho_u\alpha_u\mathbb{E}[\|\mathbf{g}_u\|^2]}{\rho_u\sum_{i\neq u}\alpha_i\mathbb{E}\left[\frac{|\mathbf{g}_u^H\mathbf{g}_i|^2}{\|\mathbf{g}_i\|^2}\right] + \rho_u\mathbb{E}[\mathrm{tr}(\mathbf{g}_u\mathbf{g}_u^H\mathbf{V})] + \rho_u\sigma_u^2 + \delta_u^2}\right). \tag{21}$$

Theorem 4: We assume that the covariance matrix of the AN $\mathbf{V}$ has uniformly bounded spectral norm, the approximate harvested power of the u-th user at EH is

$$\tilde{E}_u = \xi_u(1-\rho_u)\beta_u(\theta_{\text{tilt}})\Bigg[\alpha_u M + \sum_{i\neq u}\alpha_i \ell_{i,u} + \frac{K_u \text{tr}(\mathbf{A}_u\mathbf{V}) + \text{tr}\mathbf{V}}{K_u+1}\Bigg]. \quad (26)$$

IV. PROBLEM FORMULATION AND SOLUTIONS

In this section, we propose an iterative algorithm to improve the performance of secure communications in SWIPT by exploiting the vertical domain. We formulate the optimization problem to minimize the BS transmit power with individual secrecy rate targets and harvested power requirements. The BS antenna tilt is jointly optimized with power allocation, AN covariance, and PS ratios. The approximations derived in the previous section are used to construct this optimization problem, which will be verified to be very close to the actual values in Section V.

Mathematically, the problem is given by

$$\begin{aligned} \min_{\{\alpha_u,\rho_u\},\theta_{\text{tilt}},\mathbf{V}} \ & \sum_{u=1}^{U}\alpha_u + \text{tr}(\mathbf{V}) \\ \text{s.t. } & \tilde{R}_u \geq \check{R}_u, \quad \forall u, \\ & \tilde{E}_u \geq \check{E}_u, \quad \forall u, \\ & 0 < \rho_u < 1, \quad \forall u, \\ & \alpha_u > 0, \quad \forall u, \\ & 0 < \theta_{\text{tilt}} < \frac{\pi}{2}, \\ & \mathbf{V} \succeq 0, \end{aligned} \quad (27)$$

where the first two constraints are secrecy rate and harvested power requirements, respectively, and $\check{R}_u$ and $\check{E}_u$ are the secrecy rate and harvested power targets for the u-th user, respectively. $\tilde{R}_u$ and $\tilde{E}_u$ are given by Theorem 3 and 4, respectively. We assume that all users can fully enjoy the service of SWIPT, so $0 < \rho_u < 1$. Since the optimization variables are coupled in the constraints, (27) is nonconvex.

In this paper, we consider the scenario where at least one ED has the same AoD with the intended user. Such EDs receive highly correlated signals and they really matter in calculating the secrecy rate of the intended user. Since their ergodic achievable rates will increase with the number of BS antennas, the secrecy rate of the intended user will be affected dramatically. The other EDs whose angles of departure are different from the intended user have a negligible effect on the secrecy rate, because the beamforming in the massive MIMO systems is directional and the received signal strength at those EDs is much smaller than that at the intended user. So, when we calculate the secrecy rate in Theorem 3, $m \in \mathcal{A}_u$ which is the user set including EDs with the same AoD as the intended user, i.e, the u-th user.

In the massive MIMO systems, the received SINR of the intended user could be very large, so is that of the ED with the same AoD. Hence, the secrecy rate of the u-th user in Theorem 3 is approximated by

$$\begin{aligned} \tilde{R}_u &\approx \left[\log_2 \tilde{\gamma}_u - \max_{\forall m\in\mathcal{A}_u} \log_2 \tilde{\gamma}_{m,u}\right]^+ \\ &= \left[\log_2 \frac{\tilde{\gamma}_u}{\max_{\forall m\in\mathcal{A}_u}\tilde{\gamma}_{m,u}}\right]^+. \end{aligned} \quad (28)$$

For $\forall m \in \mathcal{A}_u$, according to Lemma 1, we have $\text{tr}(\mathbf{A}_u\mathbf{A}_m) = M^2$. Substituting it into (24), we obtain

$$\tilde{\gamma}_{m,u} = \frac{\alpha_u c_{m,u}}{\sum_{i\neq u,m}\alpha_i\ell_{i,m} + \alpha_m M + \frac{K_m\text{tr}(\mathbf{A}_m\mathbf{V})+\text{tr}\mathbf{V}}{K_m+1} + \frac{\sigma_m^2}{\beta_m(\theta_{\text{tilt}})}}, \quad (29)$$

where

$$c_{m,u} = \frac{K_u K_m M + K_m}{(K_u+1)(K_m+1)} + \frac{1}{K_m+1}. \quad (30)$$

Using Theorem 1 and (29), we expand $\frac{\tilde{\gamma}_u}{\tilde{\gamma}_{m,u}}$ in (28) as

$$\frac{\tilde{\gamma}_u}{\tilde{\gamma}_{m,u}} = \frac{M\left(\sum_{i\neq u,m}\alpha_i\ell_{i,m} + \alpha_m M + \frac{K_m\text{tr}(\mathbf{A}_m\mathbf{V})+\text{tr}\mathbf{V}}{K_m+1} + \frac{\sigma_m^2}{\beta_m(\theta_{\text{tilt}})}\right)}{c_{m,u}\left(\sum_{i\neq u}\alpha_i\ell_{i,u} + \frac{K_u\text{tr}(\mathbf{A}_u\mathbf{V})+\text{tr}\mathbf{V}}{K_u+1} + \frac{\sigma_u^2}{\beta_u(\theta_{\text{tilt}})} + \frac{\delta_u^2}{\rho_u\beta_u(\theta_{\text{tilt}})}\right)}. \quad (31)$$

Thus, (27) is transformed into

$$\begin{aligned} \min_{\{\alpha_u,\rho_u\},\theta_{\text{tilt}},\mathbf{V}} \ & \sum_{u=1}^{U}\alpha_u + \text{tr}(\mathbf{V}) \\ \text{s.t. } & \frac{\tilde{\gamma}_u}{\tilde{\gamma}_{m,u}} \geq 2^{\check{R}_u}, \quad \forall m\in\mathcal{A}_u, \ \forall u, \\ & \tilde{E}_u \geq \check{E}_u, \quad \forall u, \\ & 0 < \rho_u < 1, \quad \forall u, \\ & \alpha_u > 0, \quad \forall u, \\ & 0 < \theta_{\text{tilt}} < \frac{\pi}{2}, \\ & \mathbf{V} \succeq 0. \end{aligned} \quad (32)$$

Since we have

$$\frac{\tilde{\gamma}_u}{\tilde{\gamma}_{m,u}} \geq \frac{M\left(\sum_{i\neq u,m}\alpha_i\ell_{i,m} + \alpha_m M + \frac{K_m\text{tr}(\mathbf{A}_m\mathbf{V})+\text{tr}\mathbf{V}}{K_m+1}\right)}{c_{m,u}\left(\sum_{i\neq u}\alpha_i\ell_{i,u} + \frac{K_u\text{tr}(\mathbf{A}_u\mathbf{V})+\text{tr}\mathbf{V}}{K_u+1} + \frac{\sigma_u^2}{\beta_u(\theta_{\text{tilt}})} + \frac{\delta_u^2}{\rho_u\beta_u(\theta_{\text{tilt}})}\right)}, \quad (33)$$

the first constraint of (32) will be satisfied if

$$\frac{M\left(\sum_{i\neq u,m}\alpha_i\ell_{i,m} + \alpha_m M + \frac{K_m\text{tr}(\mathbf{A}_m\mathbf{V})+\text{tr}\mathbf{V}}{K_m+1}\right)}{c_{m,u}\left(\sum_{i\neq u}\alpha_i\ell_{i,u} + \frac{K_u\text{tr}(\mathbf{A}_u\mathbf{V})+\text{tr}\mathbf{V}}{K_u+1} + \frac{\sigma_u^2}{\beta_u(\theta_{\text{tilt}})} + \frac{\delta_u^2}{\rho_u\beta_u(\theta_{\text{tilt}})}\right)} \geq 2^{\check{R}_u}. \quad (34)$$

We reformulate the above inequality as follows:

$$2^{\check{R}_u} c_{m,u}\left(\sum_{i\neq u}\alpha_i\ell_{i,u}+\frac{K_u\mathrm{tr}(\mathbf{A}_u\mathbf{V})+\mathrm{tr}\mathbf{V}}{K_u+1}+\frac{\sigma_u^2}{\beta_u(\theta_{\mathrm{tilt}})}+\frac{\delta_u^2}{\rho_u\beta_u(\theta_{\mathrm{tilt}})}\right)-M\left(\sum_{i\neq u,m}\alpha_i\ell_{i,m}+\alpha_m M+\frac{K_m\mathrm{tr}(\mathbf{A}_m\mathbf{V})+\mathrm{tr}\mathbf{V}}{K_m+1}\right)\leq 0,\ \forall m\in\mathcal{A}_u,\quad \forall u, \tag{35}$$

The second constraint of (32) is rewritten as

$$\frac{\check{E}_u}{\xi_u(1-\rho_u)\beta_u(\theta_{\mathrm{tilt}})}-\alpha_u M-\sum_{i\neq u}\alpha_i\ell_{i,u}-\frac{K_u\mathrm{tr}(\mathbf{A}_u\mathbf{V})+\mathrm{tr}\mathbf{V}}{K_u+1}\leq 0,\quad \forall u. \tag{36}$$

Then (32) is transformed into

$$\begin{aligned}\min_{\{\alpha_u,\rho_u\},\theta_{\mathrm{tilt}},\mathbf{V}}\ &\sum_{u=1}^{U}\alpha_u+\mathrm{tr}(\mathbf{V})\\ \text{s.t. }&(35),\ (36),\\ &0<\rho_u<1,\quad\forall u,\\ &\alpha_u>0,\quad\forall u,\\ &0<\theta_{\mathrm{tilt}}<\frac{\pi}{2},\\ &\mathbf{V}\succeq 0.\end{aligned} \tag{37}$$

Both $\mathrm{tr}(\mathbf{A}_u\mathbf{V})$ and $\mathrm{tr}\mathbf{V}$ are convex functions of $\mathbf{V}$. $\frac{1}{\beta_u(\theta_{\mathrm{tilt}})}$ is a convex function of θ_{tilt}. Both $\frac{1}{\rho_u\beta_u(\theta_{\mathrm{tilt}})}$ and $\frac{1}{(1-\rho_u)\beta_u(\theta_{\mathrm{tilt}})}$ are convex functions of ρ_u and θ_{tilt} due to their positive definite Hessian matrices. Thus, (37) is convex, but it cannot be solved by optimization software tools directly due to the exponent form of θ_{tilt}.

The optimum of (37) can be derived by the brute-force search. The complexity of the brute-force search is $O(\frac{U^2}{t_\theta t_\alpha t_\rho})$, where t_θ, t_α, and t_ρ are the step sizes of antenna tilt, power allocation, and PS ratios, respectively.

The brute-force search has high computational complexity and we propose an iterative algorithm with low complexity. We apply the dual to obtain θ_{tilt}. Via the dual, ρ_u can also be presented in an analytical expression. Then α_u and $\mathbf{V}$ are solved numerically by CVX [27].

The dual problem of (37) is given by

$$\max_{\lambda_{m,u},\mu_u\geq 0}\ \min_{0<\rho_u<1,\alpha_u>0,0<\theta_{\mathrm{tilt}}<\frac{\pi}{2},\mathbf{V}\succeq 0} L(\Omega), \tag{38}$$

where $\lambda_{m,u}$ and μ_u are the nonnegative Lagrange multipliers, Ω is the collection of all the primal and dual variables of (37), and the Lagrangian $L(\Omega)$ is expressed as (39), shown at the bottom of this page.

Primal and dual optimal solutions satisfy Karush-Kuhn-Tucker (KKT) conditions and strong duality holds [28]. When dual optimal points $\{\lambda_{m,u}^*\}$ and $\{\mu_u^*\}$ are known, the optimal ρ_u^* can be derived from the KKT condition:

$$\frac{\partial L}{\partial \rho_u}=\frac{-\sum_{m\neq u}\lambda_{m,u}^* c_{m,u}2^{\check{R}_u}\delta_u^2}{\rho_u^2}+\frac{\mu_u^*\check{E}_u}{\xi_u(1-\rho_u)^2}=0. \tag{40}$$

Because $0<\rho_u<1$, we thus have

$$\rho_u^*=\frac{-a_u+\sqrt{a_u b_u}}{-a_u+b_u}, \tag{41}$$

where

$$a_u=\sum_{m\neq u}\lambda_{m,u}^* c_{m,u}2^{\check{R}_u}\delta_u^2\xi_u, \tag{42}$$

and

$$b_u=\mu_u^*\check{E}_u. \tag{43}$$

The optimal θ_{tilt}^* can be derived from the KKT condition:

$$\frac{\partial L}{\partial\theta_{\mathrm{tilt}}}=\sum_u e_u\frac{\partial\frac{1}{\beta_u(\theta_{\mathrm{tilt}})}}{\partial\theta_{\mathrm{tilt}}}=0, \tag{44}$$

where

$$e_u=\sum_{m\neq u}\lambda_{m,u}^* c_{m,u}2^{\check{R}_u}\left(\sigma_u^2+\frac{\delta_u^2}{\rho_u^*}\right)+\frac{\mu_u^*\check{E}_u}{\xi_u(1-\rho_u^*)}. \tag{45}$$

Based on (12), we have

$$\frac{\partial\frac{1}{\beta_u(\theta_{\mathrm{tilt}})}}{\partial\theta_{\mathrm{tilt}}}=-\frac{\ln 10}{10\beta_u(\theta_{\mathrm{tilt}})}\frac{\partial B_u(\theta_{\mathrm{tilt}})}{\partial\theta_{\mathrm{tilt}}}, \tag{46}$$

where

$$\frac{\partial B_u(\theta_{\mathrm{tilt}})}{\partial\theta_{\mathrm{tilt}}}=\begin{cases}\frac{24}{\theta_{3\mathrm{dB}}^2}(\theta_{\mathrm{tilt}}-\theta_u), & \text{if } 12\left(\frac{\theta_u-\theta_{\mathrm{tilt}}}{\theta_{3\mathrm{dB}}}\right)^2<\mathrm{SLL_{el}}\\ 0, & \text{else}\end{cases}$$

So, with (44), the optimal θ_{tilt}^* satifies

$$\sum_{u\in\mathcal{S}}e_u\frac{(\theta_{\mathrm{tilt}}^*-\theta_u)}{\beta_u(\theta_{\mathrm{tilt}}^*)}=0, \tag{47}$$

$$\begin{aligned}L(\Omega)=&\sum_u\alpha_u+\mathrm{tr}(\mathbf{V})+\sum_u\sum_{m\neq u}\lambda_{m,u}\left\{2^{\check{R}_u}c_{m,u}\left(\sum_{i\neq u}\alpha_i\ell_{i,u}+\frac{K_u\mathrm{tr}(\mathbf{A}_u\mathbf{V})+\mathrm{tr}\mathbf{V}}{K_u+1}+\frac{\sigma_u^2}{\beta_u(\theta_{\mathrm{tilt}})}+\frac{\delta_u^2}{\rho_u\beta_u(\theta_{\mathrm{tilt}})}\right)-M\right.\\ &\left.\times\left(\sum_{i\neq u,m}\alpha_i\ell_{i,m}+\alpha_m M+\frac{K_m\mathrm{tr}(\mathbf{A}_m\mathbf{V})+\mathrm{tr}\mathbf{V}}{K_m+1}\right)\right\}+\sum_u\mu_u\left\{\frac{\check{E}_u}{\xi_u(1-\rho_u)\beta_u(\theta_{\mathrm{tilt}})}-\alpha_u M-\sum_{i\neq u}\alpha_i\ell_{i,u}\right.\\ &\left.-\frac{K_u\mathrm{tr}(\mathbf{A}_u\mathbf{V})+\mathrm{tr}\mathbf{V}}{K_u+1}\right\}\end{aligned} \tag{39}$$

where $\mathcal{S} = \left\{u \middle| 12\left(\frac{\theta_u-\theta_{\text{tilt}}}{\theta_{3\text{dB}}}\right)^2 < \text{SLL}_{\text{el}}\right\}$. Let $f(\theta_{\text{tilt}}) = \sum_{u\in\mathcal{S}} e_u \frac{(\theta_{\text{tilt}}-\theta_u)}{\beta_u(\theta_{\text{tilt}})}$ which is a monotonically increasing function with $f(0) < 0$ and $f(\frac{\pi}{2}) > 0$. So, we can use bisection method to find θ_{tilt}^* and adopt the exhaustive search to check whether a user belongs to $\mathcal{S}$. The optimal solutions $\{\alpha_u^*\}$ and $\mathbf{V}^*$ can be obtained by CVX with $\{\lambda_{m,u}^*\}$, $\{\mu_u^*\}$, $\{\rho_u^*\}$, and θ_{tilt}^*.

We use the Polyak's subgradient method to solve the dual problem [29]. The Lagrange multipliers are respectively given by

$$\lambda_{m,u}^{k+1} = \left[\lambda_{m,u}^k + t^k \triangle\lambda_{m,u}^k\right]^+, \tag{48}$$

$$\mu_u^{k+1} = \left[\mu_u^k + t^k \triangle\mu_u^k\right]^+, \tag{49}$$

where k is the iteration index, t^k is the step size. $\triangle\lambda_{m,u}^k$ and $\triangle\mu_u^k$ are the subgradients which are respectively given by

$$\begin{aligned}\triangle\lambda_{m,u}^k = 2^{\check{R}_u} c_{m,u}\Bigg(&\sum_{i\neq u}\alpha_i^k \ell_{i,u} + \frac{K_u \text{tr}(\mathbf{A}_u\mathbf{V}^k)+\text{tr}\mathbf{V}^k}{K_u+1} \\ &+\frac{\sigma_u^2}{\beta_u(\theta_{\text{tilt}}^k)}+\frac{\delta_u^2}{\rho_u^k\beta_u(\theta_{\text{tilt}}^k)}\Bigg)-M\Bigg(\sum_{i\neq u,m}\alpha_i^k\ell_{i,m}+\alpha_m^k M \\ &+\frac{K_m\text{tr}(\mathbf{A}_m\mathbf{V}^k)+\text{tr}\mathbf{V}^k}{K_m+1}\Bigg),\end{aligned} \tag{50}$$

$$\begin{aligned}\triangle\mu_u^k = &\frac{\check{E}_u}{\xi_u(1-\rho_u^k)\beta_u(\theta_{\text{tilt}}^k)} - \alpha_u^k M - \sum_{i\neq u}\alpha_i^k\ell_{i,u} \\ &- \frac{K_u\text{tr}(\mathbf{A}_u\mathbf{V}^k)+\text{tr}\mathbf{V}^k}{K_u+1}.\end{aligned} \tag{51}$$

where $\{\rho_u^k\}$, $\{\alpha_u^k\}$, θ_{tilt}^k, and $\mathbf{V}^k$ are the optimums when $\lambda_{m,u}^k$ and μ_u^k are given.

An iterative algorithm is summarized as follows. The stopping criterion is set to be the maximum number of iterations.

Algorithm 1 The Iterative Algorithm for (27)

1: Initialize $\lambda_{m,u}^1$, μ_u^1, $\forall m \in \mathcal{A}_u$, $\forall u$
2: **for** $k = 2, \ldots, N$, where N is the maximum number of iterations, **do**
3: With $\lambda_{m,u}^{k-1}$, μ_u^{k-1}, obtain ρ_u^k and θ_{tilt}^k via (41) and (47), respectively.
4: With θ_{tilt}^k, ρ_u^k, $\lambda_{m,u}^{k-1}$, and μ_u^{k-1}, use CVX to get α_u^k and $\mathbf{V}^k$.
5: With θ_{tilt}^k, ρ_u^k, α_u^k, and $\mathbf{V}^k$, update $\lambda_{m,u}^k t$ and μ_u^k by (48) and (49), respectively.
6: **end for**
7: $\theta_{\text{tilt}}^* = \theta_{\text{tilt}}^N$, $\rho_u^* = \rho_u^N$, $\alpha_u^* = \alpha_u^N$, $\mathbf{V}^* = \mathbf{V}^N$.

The complexity of our proposal mainly comes from the tilt optimization including exhaustive search for user set $\mathcal{S}$ and bisection method. The number of possibilities of the user set $\mathcal{S}$ is $\sum_{u=1}^{U}\binom{U}{u}$. For each possible user set, we firstly calculate (47), secondly apply bisection method for tilt, and then check whether $12\left(\frac{\theta_u-\theta_{\text{tilt}}}{\theta_{3\text{dB}}}\right)^2 < \text{SLL}_{\text{el}}$ is satisfied. Altogether, the total complexity is $O((U^2 - \log_2\ t_\theta)N2^U)$. We observe that the computational complexity of our proposal is lower than that of the brute-force search.

When the proposed algorithm is implemented in practice, the BS requires the large-scale channel state information (CSI) and the geographical coordinates via global positioning system (GPS). We can use the low-rate feedback link to obtain the CSI, due to the slow change rate of the user location information. After the proposed algorithm is done, the BS sends the optimized PS ratios to users, and employs the power allocation and the AN covariance for SWIPT. Besides, the optimized antenna tilt can be adjusted electrically via changing the phase of antenna excitation [30].

V. SIMULATION RESULTS

In this section, we evaluate the performance of our proposed algorithm which exploits the vertical domain for secure SWIPT in massive MIMO systems. For all results, we assume that the horizontal and vertical angles of the u-th user ϕ_u and θ_u are randomly chosen in the range of $[-\pi, \pi]$ and $[0, \frac{\pi}{2}]$, respectively. The standard deviation of the shadowing is $\sigma_{\text{shad}} = 8$ dB. The maximum distance between the BS and users is 10 m and the path loss exponent is $\upsilon = 3.8$. The antenna noise power is $\sigma_k^2 = -70$ dBm and the noise power at ID is $\delta_k^2 = -50$ dBm [5]. In the antenna pattern, the horizontal and vertical 3 dB beamwidths are $\phi_{3\text{dB}} = 65°$ and $\theta_{3\text{dB}} = 6°$, respectively. The sidelobe levels of the horizontal and vertical BS antenna patterns are $\text{SLL}_{\text{az}} = 25$ dB and $\text{SLL}_{\text{el}} = 20$ dB, respectively. The Rician K-factor is $K_u = 1$ for all users.

First, we verify the approximate ergodic achievable secrecy rate of the u-th user expressed in Theorem 3. The parameter configuration is set as follows. The number of users is $U = 10$. The number of BS antennas M is varied in the range of [10, 100]. We assume that the antenna tilt is fixed as $\theta_{\text{tilt}} = 8°$ [31], the allocated transmit power α_u is randomly chosen in [0.1, 1] W, the PS ratio is $\rho_u = 0.1, \forall u$. The AoD ψ_u in the deterministic component of the Rician channel is randomly changed in $[0, 2\pi]$. Without loss of generality, we investigate the 1st user who is the intended user. We let the AoD of the 2nd user be the same with the 1st user. The simulated and approximate ergodic achievable rates of these two users are all shown in Fig. 2. The simulated results of the 1st user and the 2nd user are given in (7) and (8), respectively, which are the actual rates. The approximate ones are given in Theorem 1 and 2, respectively. We also present the secrecy rate of the 1st user according to Theorem 3. Evidently, the approximations are very close to the actual results, thanks to the properties of massive MIMO systems. So, it is valid that the optimization problem and the proposal are based on the approximations. Furthermore, with the increasing number of BS antennas, the achievable rates of both users are growing. The underlying reason for this phenomenon is that the ED receives a highly correlated signal in this LoS scenario when the corresponding AoD is the same with that of the intended user. We also find that the 2nd user has the maximum

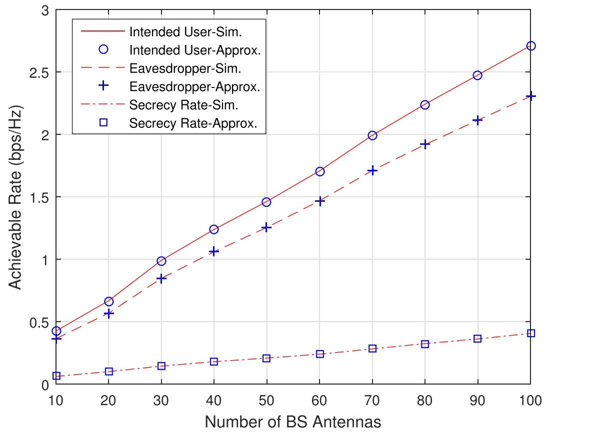

FIGURE 2. Achievable rates of the intended user at ID and the ED with the same AoD, and the secrecy rate of the intended user (bps/Hz) versus number of BS antennas. The approximations are very tight with the actual values.

achievable rate among the $U-1$ EDs. Hence, this kind of ED causes the most serious impact on the secrecy rate and we resort to the 3-D antenna technique to alleviate this problem.

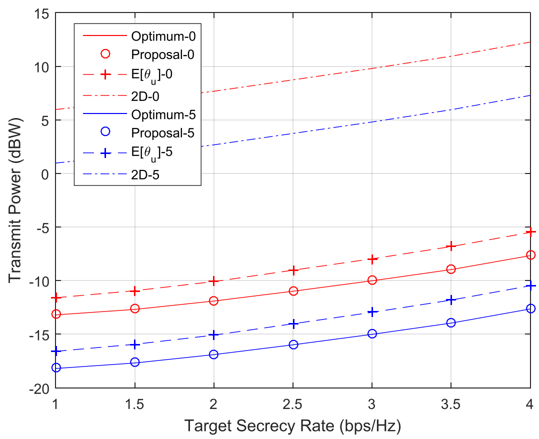

FIGURE 3. BS transmit power (dBW) versus target secrecy rate (bps/Hz) with fixed harvested power constraints $\breve{E} = 0$ dBm and -5 dBm.

Then we investigate the performance of the proposed algorithm. For comparison, the optimum from the brute-force search is simulated. The adaptive antenna tilt in a conventional 3-D MIMO system is also considered here, which is the mean of the vertical angles of all users, i.e., $\theta^*_{\text{tilt}} = \mathbb{E}[\theta_u]$ [32]. Besides, we simulate the 2-D scheme with a fixed antenna tilt $\theta_{\text{tilt}} = 8°$. When the antenna tilt is given, the power allocation, AN covariance, and PS ratios are jointly optimized via CVX. We assume that the energy conversion efficiency at the EH is $\xi_u = 0.5$ for all users. The target secrecy rate is $\breve{R}_u = \breve{R}, \forall u$ and the target harvested power is $\breve{E}_u = \breve{E}, \forall u$. The number of BS antennas is $M = 100$. The performance of the BS transmit power with varying secrecy rate target is illustrated in Fig. 3. The harvested power target $\breve{E}$ is fixed as 0 dBm and -5 dBm, which are denoted by "-0" and "-5" in Fig. 3, respectively. We find that with the increasing secrecy rate target, the transmit power becomes higher. Fig. 4 shows the impact of the harvested power target on the BS transmit power. The secrecy rate target $\breve{R}$ is fixed as 1 bps/Hz and 3 bps/Hz, which are denoted by "-1" and "-3" in Fig. 4, respectively. Obviously, larger harvested power targets require more BS transmit power. These two figures both verify that the proposed algorithm has a quite good performance which is close to that of the optimum and outperforms the 2-D and conventional 3-D MIMO schemes. Therefore, the tilt adaptation plays a significant role in secure SWIPT by exploiting the vertical domain.

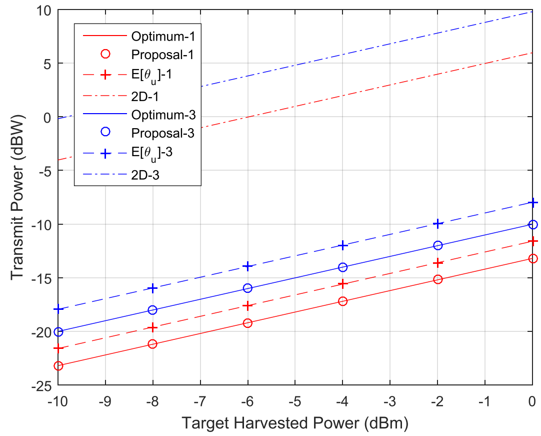

FIGURE 4. BS transmit power (dBW) versus target harvested power (dBm) with fixed secrecy rate constraints $\breve{R} = 1$ bps/Hz and 3 bps/Hz.

VI. CONCLUSION

We considered a 3-D massive MIMO SWIPT system with Rician fading channels. At least one ED has the same AoD with the intended user. We adopted 3-D directional antennas and adjusted the antenna tilt to improve the secrecy rate and harvested energy. The approximate secrecy rate and harvested energy were derived and verified to be very close with the actual values through numerical results. The optimization problem aims at minimizing the BS transmit power with the constraints of secrecy rate and harvested energy. The problem is nonconvex and the presence form of the optimization variable, the antenna tilt, cannot be solved by using optimization software tools directly. We proposed an iterative algorithm to jointly optimize the antenna tilt, power allocation, AN covariance, and PS ratios. Simulations show that the performance of the proposal approaches to that of the optimum from the brute-force search and outperforms the 2-D and conventional 3-D MIMO schemes.

APPENDIX
PROOF OF LEMMA 3

For two different users, i.e., the u-th user and the i-th user, $u \neq i$, using (11) and (14), we obtain

$$\begin{aligned}\mathbb{E}\left[\frac{|\mathbf{g}_u^H\mathbf{g}_i|^2}{\|\mathbf{g}_i\|^2}\right] &= \mathbb{E}\left[\mathbf{g}_u^H\frac{\mathbf{g}_i\mathbf{g}_i^H}{\|\mathbf{g}_i\|^2}\mathbf{g}_u\right]\\ &= \beta_u(\theta_{\text{tilt}}) \times \mathbb{E}\left[\frac{K_u}{K_u+1}\bar{\mathbf{h}}_u^H\frac{\mathbf{g}_i\mathbf{g}_i^H}{\|\mathbf{g}_i\|^2}\bar{\mathbf{h}}_u\right.\\ &\quad\left.+\frac{1}{K_u+1}\mathbf{h}_{\omega,u}^H\frac{\mathbf{g}_i\mathbf{g}_i^H}{\|\mathbf{g}_i\|^2}\mathbf{h}_{\omega,u}\right], \qquad (52)\end{aligned}$$

where

$$\mathbb{E}\left[\bar{\mathbf{h}}_u^H \frac{\mathbf{g}_i\mathbf{g}_i^H}{\|\mathbf{g}_i\|^2}\bar{\mathbf{h}}_u\right] = \mathbb{E}\left[\mathrm{tr}\left(\frac{\mathbf{g}_i\mathbf{g}_i^H}{\|\mathbf{g}_i\|^2}\mathbf{A}_u\right)\right] = \mathbb{E}\left\{\mathrm{tr}\left[\left(\frac{K_i}{K_i+1}\mathbf{A}_i + \frac{1}{K_i+1}\mathbf{h}_{\omega,i}\mathbf{h}_{\omega,i}^H\right)\frac{\mathbf{A}_u}{\|\mathbf{h}_i\|^2}\right]\right\}. \quad (53)$$

Using the law of large numbers, we have

$$\lim_{M\to\infty}\frac{\|\mathbf{h}_i\|^2}{M} \to 1, \quad (54)$$

so in (53),

$$\mathbb{E}\left[\mathrm{tr}\left(\frac{K_i\mathbf{A}_i\mathbf{A}_u}{(K_i+1)\|\mathbf{h}_i\|^2}\right)\right] \approx \frac{K_i}{M(K_i+1)}\mathrm{tr}\left(\mathbf{A}_i\mathbf{A}_u\right). \quad (55)$$

Because the spectral norm of $\frac{\mathbf{A}_u}{M}$ is 1, based on Lemma 1 and [21, Lemma 4 (ii)], we have

$$\mathrm{tr}\left(\frac{\mathbf{h}_{\omega,i}\mathbf{h}_{\omega,i}^H\mathbf{A}_u}{\|\mathbf{h}_i\|^2}\right) = \frac{\mathbf{h}_{\omega,i}^H\frac{\mathbf{A}_u}{M}\mathbf{h}_{\omega,i}}{\frac{\|\mathbf{h}_i\|^2}{M}} \asymp \frac{\mathrm{tr}(\mathbf{A}_u)}{M} = 1. \quad (56)$$

where $a_n \asymp b_n$ denotes the equivalence relation $a_n - b_n \xrightarrow[n\to\infty]{a.s.} 0$ for two infinite sequences a_n and b_n, and $\xrightarrow[n\to\infty]{a.s.}$ means almost sure convergence.

Thus, (53) is approximated by

$$\mathbb{E}\left[\bar{\mathbf{h}}_u^H \frac{\mathbf{g}_i\mathbf{g}_i^H}{\|\mathbf{g}_i\|^2}\bar{\mathbf{h}}_u\right] \approx \frac{K_i\mathrm{tr}\left(\mathbf{A}_i\mathbf{A}_u\right)+M}{M(K_i+1)} \quad (57)$$

Similarly, in (52), since the spectral norm of $\frac{\mathbf{g}_i\mathbf{g}_i^H}{\|\mathbf{g}_i\|^2}$ is 1, we have

$$\mathbf{h}_{\omega,u}^H\frac{\mathbf{g}_i\mathbf{g}_i^H}{\|\mathbf{g}_i\|^2}\mathbf{h}_{\omega,u} \asymp 1. \quad (58)$$

So, (17) is obtained by combining (57) and (58).

REFERENCES

[1] L. R. Varshney, "Transporting information and energy simultaneously," in *Proc. IEEE Int. Symp. Inf. Theory*, Toronto, ON, Canada, Aug. 2008, pp. 1612–1616.

[2] S. Jang, H. Lee, S. Kang, T. Oh, and I. Lee, "Energy efficient SWIPT systems in multi-cell MISO networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 12, pp. 8180–8194, Dec. 2018.

[3] M. R. A. Khandaker, C. Masouros, K.-K. Wong, and S. Timotheou, "Secure SWIPT by exploiting constructive interference and artificial noise," *IEEE Trans. Commun.*, to be published.

[4] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng, and R. Schober, "Simultaneous wireless information and power transfer in modern communication systems," *IEEE Commun. Mag.*, vol. 52, no. 11, pp. 104–110, Nov. 2014.

[5] Q. Shi, L. Liu, W. Xu, and R. Zhang, "Joint transmit beamforming and receive power splitting for MISO SWIPT systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 6, pp. 3269–3280, Jun. 2014.

[6] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.

[7] A. D. Wyner, "The wiretap channel" *Bell Syst. Tech. J.*, vol. 54, no. 8, pp. 1355–1387, Oct. 1975

[8] R. Negi and S. Goel, "Secret communication using artificial noise," in *Proc. IEEE Veh. Technol. Conf. (VTC)*, Sep. 2005, pp. 1906–1910.

[9] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3590–3600, Nov. 2010.

[10] G. Yang, C. K. Ho, R. Zhang, and Y. L. Guan, "Throughput optimization for massive MIMO systems powered by wireless energy transfer," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 8, pp. 1640–1650, Aug. 2015.

[11] D. Kapetanovic, G. Zheng, and F. Rusek, "Physical layer security for massive MIMO: An overview on passive eavesdropping and active attacks," *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 21–27, Jun. 2015.

[12] L. Wang, K.-K. Wong, M. Elkashlan, A. Nallanathan, and S. Lambotharan, "Secrecy and energy efficiency in massive MIMO aided heterogeneous C-RAN: A new look at interference," *IEEE J. Sel. Topics Signal Process.*, vol. 10, no. 8, pp. 1375–1389, Dec. 2016.

[13] M. Alageli, A. Ikhlef, and J. Chambers, "SWIPT massive MIMO systems with active eavesdropping," *IEEE J. Sel. Areas Commun.*, vol. 37, no. 1, pp. 233–247, Jan. 2018.

[14] J. Zhang, C. Yuen, C.-K. Wen, S. Jin, K.-K. Wong, and H. Zhu, "Large system secrecy rate analysis for SWIPT MIMO wiretap channels," *IEEE Trans. Inf. Forensics Security*, vol. 11, no. 1, pp. 74–85, Jan. 2016.

[15] J. Zhu, Y. Li, N. Wang, and W. Xu, "Wireless information and power transfer in secure massive MIMO downlink with phase noise," *IEEE Wireless Commun. Lett.*, vol. 6, no. 3, pp. 298–301, Jun. 2017.

[16] Q.-U.-A. Nadeem, A. Kammoun, M. Debbah, and M.-S. Alouini, "3D massive MIMO systems: Modeling and performance analysis," *IEEE Trans. Wireless Commun.*, vol. 14, no. 12, pp. 6926–6939, Dec. 2015.

[17] I. Krikidis, "SWIPT in 3-D bipolar ad hoc networks with sectorized antennas," *IEEE Commun. Lett.*, vol. 20, no. 6, pp. 1267–1270, Jun. 2016.

[18] N. Seifi, M. Coldrey, and M. Viberg, "Throughput optimization for MISO interference channels via coordinated user-specific tilting," *IEEE Commun. Lett.*, vol. 16, no. 8, pp. 1248–1251, Aug. 2012.

[19] N. Seifi, J. Zhang, R. W. Heath, Jr., T. Svensson, and M. Coldrey, "Coordinated 3D beamforming for interference management in cellular networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 10, pp. 5396–5410, Oct. 2014.

[20] L. Fan, H. Zhang, Y. Huang, and L. Yang, "Exploiting BS antenna tilt for SWIPT in 3-D massive MIMO systems," *IEEE Wireless Commun. Lett.*, vol. 6, no. 5, pp. 666–669, Oct. 2017.

[21] J. Hoydis, S. ten Brink, and M. Debbah, "Massive MIMO in the UL/DL of cellular networks: How many antennas do we need?" *IEEE J. Sel. Areas Commun.*, vol. 31, no. 2, pp. 160–171, Feb. 2013.

[22] J. Lei, Z. Han, M. Á. Vazquez-Castro, and A. Hjorungnes, "Secure satellite communication systems design with individual secrecy rate constraints," *IEEE Trans. Inf. Forensics Security*, vol. 6, no. 3, pp. 661–671, Sep. 2011.

[23] *Further Advancements for E-UTRA Physical Layer Aspects*, document TR 36.814 V9.0, 3GPP, Sophia Antipolis, France, Mar. 2010.

[24] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. New York, NY, USA: Cambridge Univ. Press, 2005.

[25] N. Ravindran, N. Jindal, and H. C. Huang, "Beamforming with finite rate feedback for LOS MIMO downlink channels," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Nov. 2007, pp. 4200–4204.

[26] Q. Zhang, S. Jin, K.-K. Wong, H. Zhu, and M. Matthaiou, "Power scaling of uplink massive MIMO systems with arbitrary-rank channel means," *IEEE J. Sel. Topics Signal Process.*, vol. 8, no. 5, pp. 966–981, Oct. 2014.

[27] M. Grant and S. Boyd. *The CVX Users' Guide*. CVX Research, Inc. Accessed: Dec. 15, 2018. [Online]. Available: http://web.cvxr.com/cvx/doc/CVX.pdf

[28] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[29] B. Polyak, *Introduction to Optimization*. New York, NY, USA: Optimization Software, Inc., 1987.

[30] J. Koppenborg, H. Halbauer, S. Saur, and C. Hoek, "3D beamforming trials with an active antenna array," in *Proc. Int. ITG Workshop Smart Antennas*, Dresden, Germany, Mar. 2012, pp. 110–114.

[31] A. C. Ruiz, "LTE mobile network performance with antenna tilt considering real radiation patterns," M.S. thesis, School Inf. Commun. Technol., KTH, Stockholm, Sweden, 2015.

[32] W. Lee, S.-R. Lee, H.-B. Kong, S. Lee, and I. Lee, "Downlink vertical beamforming designs for active antenna systems," *IEEE Trans. Commun.*, vol. 62, no. 6, pp. 1897–1907, Jun. 2014.

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